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A.I. IN SPACE: PAST, PRESENT, AND POSSIBLE FUTURES

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Abstract

While Artificial Intelligence (AI) has become increasingly present in recent space applications, new missions being planned will require even more incorporation of AI techniques. In this paper, we survey some of the progress made to date in implementing such programs, some current directions and issues, and speculate about the future of AI in space scenarios. We also provide examples of how thinkers from the realm of science fiction have envisioned AI's role in various aspects of space exploration.*

**Dedicated to Dr. Isaac Asimov: scientist, writer, visionary, friend.*

Introduction

As humans venture further away from Earth, the need for autonomous systems, and hence capabilities developed for **artificial Intelligence (AI)**, will increase dramatically. The increased danger inherent in longer duration missions, among other reasons, will make the role of AI essential -- e.g., to avoid or minimize the need for humans on such missions, and to augment the abilities of those humans still present. In this paper, we discuss some of the applications already developed for space applications, then venture further into the hypothetical future to discuss how various domains of space investigation might benefit from AI.

Environment Maintenance

Several AI systems have been successfully developed and deployed to **control and/or diagnose space-related environments**, e.g., to ensure that hardware and software are performing within desired parameters, and finding the cause of faults when they occur. For example, diagnosis as well as control of hardware and software has also been proven in **expert systems**, such as g2 (developed by Gensym Corp.). The later has been used to control and diagnose environments such as BioSphere 2 (BS2) and the Space Shuttle. BioSphere 2, in particular, provides an excellent testing ground for AI systems that will soon be needed in space, especially Lunar Base applications, since BS2 is an enclosed self-sufficient habitat that happens to be on Earth. Hence, knowledge learned by applying AI code in BS2 should be almost directly applicable to upcoming Lunar Base mission, and eventually Mars habitats as well.

Whereas the above examples focus on AI applied to monitoring and diagnosis of entire environments involving several interacting systems, researchers have also developed and deployed many **subsystem-specific programs for device and vehicle diagnosis**. In fact, these make up some of the most common and successful applications of AI to space domains to date. For example, NASA has used a system called PI-IN-A BOX to automate the diagnosis of equipment failure about the Space Shuttle. Another NASA project has been automating the diagnosis of a specific Shuttle subsystem (the Reaction Control System). This latter system is currently being tested on the ground, and will probably evolve into a system for use by ground-based mission controllers - but a later more advanced version of this RCS diagnostician could wind up on the Shuttle or its descendant craft. Rockwell International has also been constructing expert systems, to diagnose other parts of the Shuttle such as its fuel cell and heaters.

In summary, AI has already made valuable contributions to this field, and increases in flight duration and craft complexity (e.g., the Space Station with its 30 year life span, as well as Lunar vehicles and habitats designed for continuous long-duration use) will make sophisticated "artificial diagnosticians" even more essential. In particular, programs will have to help unmanned vehicles repair themselves if needed, such as during unmanned rover "field trips". Current **machine learning (ML)** techniques, which have already been used to augment diagnosis systems, should help in this regard. For example, ML can be used to help predict impending faults *before* they occur, so that system disruptions and downtime can be minimized. (Fans of the film *2001* [Clarke 1968] might note that the HAL 9000 computer exhibited such a capability, when it informed its crewmates that an antenna was about to fail.) In general, the use of AI technology for diagnosis will greatly decrease the need for EVAs that are not related to purely scientific objectives.

Traversing Extraterrestrial Sites

Assuming that one's hardware and software are functioning normally, one of the most important tasks to do next is exploration. This includes deciding which site should be investigated -- e.g., deciding which areas have greatest potential for scientific results and estimating the likely danger in getting there -- and then actually traversing to the sites of interest.

Telerobotics (TR) could be used to decrease the number of human EVAs required on space missions. In fact, Marvin Minsky (a father of both AI and TR) observed that, if we had thought ahead, we could have had an inexpensive teleoperated rover doing meaningful traverses on the moon for the *two decades* that have elapsed since humans last left a footprint on our satellite. Since this indeed seems a cost effective option, especially in relation to other proposed missions, we should certainly reexamine its use today as attention is refocused on the moon.

TR is part of the larger field of telepresence, itself a subarea of **Virtual Reality (VR)**. The idea here is to put a human "virtually" in some dangerous locale (e.g., space) via one or more robots, which provide the virtual eyes and perform tasks with virtual limbs as the human remains in a safe haven. Intelligent software will be needed to develop effective teleprensence capabilities - mainly via ground control in the near-term, but applicable in several space-based domains in the not-too-distant future. For instance, to decrease human risks in constructing and maintaining Space Station Freedom or remote interplanetary bases, a human could operate a robotic repair droid remotely from inside the Station, or from inside a habitat if the locale is a remote lunar or Martian site. Also note that, for relatively "terraclose" applications (ranging from Earth to locations near the Moon) one could even perform teleoperations from Earth itself without appreciable lag.

As far as longer-term longer-range robotics applications are concerned, one of the most exciting will be the return of our presence to the Moon and Mars. A major player in the latter domain is JPL, which has been developing **Intelligent robots** to roam the Martian surface or other extraterrestrial sites in a way that can maximize scientific gain while minimizing time and danger to a mission. Looking further ahead, several intriguing and challenging issues are unfolding for robotic space domains. One general issue involves deciding on the best approach to designing and deploying robots, for both nearby and remote Voyager-like space missions. One of the most common ideas has been to build one or a few robots with complex, intelligent processing onboard each one.

However, an alternate approach, favored by researchers such as MIT's Rodney Brooks, would use of tens or even hundreds of smaller, less (individually) intelligent robots per mission. One advantage of using an army of "**dumbots**" would be increased fault-tolerance. If you lose one robot, many others remain to finish the mission goals. Another approach would use one or more self-replicating robots. In fact, this latter idea might lead to a compromise between the first two approaches; one could deploy a small number of Intelligent "**replibots**" which would create small dumbots during a mission, even replace those that fail as needed. The longer the duration of a mission, such as an extended stay at a lunar or Martian base, the more important replication or automated droid production becomes.

Scientific Investigation

Once a human or machine is actually at a potentially valuable site, the priorities for AI applications shift to actual scientific tasks, such as chemical analyses, deciding which samples to carry back to a habitat or spacecraft, etc.

One fruitful area of AI that applies to these and other scientific tasks is the field of **data analysis and discovery**. Several programs have been developed in this category. For example, NASA scientists have constructed and are refining the AUTOCLASS system, which automatically classifies data into meaningful groups. Its use to date has included classifying well known star classes, as well as discovering new astronomical classes (e.g., separating data into classes having only very subtle differences in spectra). Such systems not only can lead to new knowledge, as just described, but will become *essential* for sifting through the mounting quantities of mission data being gathered from space missions.

AUTOCLASS and other AI systems should aid efforts being made in the general area of "**ground-based space exploration**'. Including projects such as SETI (the Search for Extraterrestrial Intelligence), which begins a vastly enhanced search in fall 1992. Sifting through mounds of extraterrestrial data and noise for meaningful intelligent signals seems like an ideal challenge for AUTOCLASS or related systems.

Past Looks Into the Future: Science Fiction and Speculation on Space AI

Science Fiction (**SF**) preceded science fact in most major qualitative aspects of computers -- such as artificial intelligence, robotics, and their application to space missions. (Our reference section, while extensive, represents only the tip of the iceberg.) Since SF has a long tradition of predicting ideas and inventions that ultimately materialize in our real world, we now survey some of the views SF has put fort regarding AI and its role in space exploration.

The legacy of Isaac Asimov, one of SF's best known progeny (who passed on as this paper was being prepared), includes many concepts that influenced AI, such as the invention of the word **robotics**, and the famous "Three Laws" that he (followed by countless others) felt should govern their use. Asimov also influenced generations of scientists and technologists, such as Marvin Minsky, himself one of the top experts in robotics and a pioneer of both AI and telepresence.

SF, of course, has supplied numerous other concepts that have influenced the ideas and lexicon of real AI. The original word **robot**, from the Czech "robota" (laborer), originated in a stage play [Capek 1921]. SF also provided the related term **android** (hence the contraction **droid**), meaning a robot with a humanoid appearance or, more commonly, an artificially created organic humanoid [Williamson 1936]. In addition, SF predicted teleoperation with the concept of **waldo** [Heinlein 1942], a word subsequently adopted when the technology actually came into existence years later.

Taking a more general view, SF has expanded the role of literature (and hence our cultural collective consciousness) beyond "just people", to the utilization of computers (especially those artificially intelligent) as personalities worthy of storytelling -- as well as debate and analysis.

Some examples of computers and artificial intelligences with proper names [Jakubowski 1983] who appear in stories and books include: **Abel** [Durell], **Bossy** [Clifton 1957], **Colossus** [Jones 1967], **Domino** [Budrys 1978], **Epicac XIV** [Vonnegut 1952], **Epikistes** [Lafferty], **Extro** [Bester 1974], **HAL 9000** [Clarke 1968], **Harlie** [Gerrold 1972], **Mike** [Heinlein 1966], **Multivac** [Asimov], **Proteus** [Koontz], **Shalmaneser** [Brunner 1968], **Tench 889B** [Dick], and **Unicomp** [Levin].

Some of these computer intelligences exist as faithful companions, dedicated to serving humans -- while others are imagined to lead to mad, megalomaniac, or godlike capabilities. In *Destination Void* and *The Jesus Incident* [Herbert 1966; Herbert & Ransom 1979], AI systems in space evolve to a trans-human and theological power. In "Going Down Smooth" [Silvergerg] a computer slips into psychosis, but does a credible job as a psychiatrist -- a profession that certainly might prove valuable on long missions if physical human presence continues in space.

Although we have seen AI computers as fictional personalities, science fiction admits to a favoritism for intelligent robots. Here are a dozen examples: **Adam Link** [Binder], **Brillo** [Bova & Ellison], **Helen O'Loy** [del Rey], **Jasperodus** [Bayley 1974], **Jay Score** [Russell 1955], **Jenkins** [Simak 1944], **Krag** [Hamilton 1940], **Marvin** [Adams], **R. Daneel Olivaw** [Asimov 1954], **Roderick** [Slakek], **Spofforth** [Tevis], and **Tik-Tok** [Baum].

In literary roots, AI and robotics have co-existed as concepts. It is therefore fitting that AI systems for space, which are robotic in the broad sense that they are part of highly mobile vehicles (spaceships), fulfill the emotional connection of these two concepts in a century of imaginative fiction. In fact, teleoperation and telerobotics (spawned from progress in AI and robotics) are currently active themes in SF literature [Mixon 1992].

Then, of course, there are the movies and television, which arguably have had the greatest impact on how our culture has perceived the growing use of computers and AI. Several films, such as *Silent Running* and *Star Wars*, feature nonhumanoid robots assisting humans in space, a role that much of our culture seems to accept as the most likely future scenario.

However, even though our technology will likely make such human-robot scenarios feasible, the need to have humans in space *at all* will become a growing issue as AI's power increases. Such an "AI only" view (i.e., **using only artificial hardware and software in space**) has received increasing attention from SF writers today. Although this scenario would depart from our "humans conquering space by being in space" paradigm, it would likely be safer, less costly, and ultimately more democratic if combined with telepresence's ability to *let everyone share in the exploration* [Sterling 1992].

As of May 1992, the NASA channel is already being planned for wider cable access in the U>S>; perhaps this is just the first step. Future couch potatoes might spend a day making new remote space observations on Europa (using AI in the TV to alert them to images that match interesting criteria), flicking the remote (pun intended?) to see how Mars is doing, and still have time left to watch MTV. Two researchers, located on different parts of the globe (or one on Earth one on the Moon), could us VR gear to virtually explore a more distant orb together, their telepresences being in the same remote locale although they were not. Going further, if these two were a couple, they could switch to another remote planet and have sex, virtually -- without leaving their home *or* physically touching their partners! (Then they could complain to their artificial shrinks -- "We're just not *close* anymore, Eliza").

Note that a slightly different, darker take on this remote exploration via AI was put forth on a recent *Star Trek* episode, in which an alien artificially increased the intelligence of other races (in this case, a human on the *Enterprise*) to enable them to make inventive leaps necessary to visit the alien's world. A revised version of this seems a worthy and feasible goal for our own AI. For instance, we might be able to build robots intelligent enough to *utilize elements encountered in space to better their collective situation* -- e.g., to replicate themselves, or even to improve themselves (with tasks such as detecting and extracting more efficient fuel, or simply gaining more of their current fuel). Even if we simply send out multitudes of robots and get back lots of visual data, telepresence experiences, and returned samples, we would still be "**bringing space to us**" without leaving our home, as did the alien in that *Trek* episode.

While many androids have appeared in film and TV, an interesting case is Ulysses from *Making Mr Right*; this droid was designed for space travel as a safe substitute for man, superior in mental facility as well as in its immunity to loneliness and other human "frailties". However, Ulysses, once sentient, soon wants to experience love and stay on Earth. This raises an interesting question: *might AI progress to the point where an intelligence might not want to follow it programming* (i.e., its orders/mission)? This issue was also raised in *Trek*, when Data (another android longing for humanity) is ordered to be dismantled for scientific study but a court rules him to be alive, sentient, and worthy of rights. And of course there is HAL in *2001*, which decided to deviate from some of its orders as well. In short, there may come a point in the future when software designers will have the twin constraints of needing software that is intelligent enough to do vital tasks, but not smart enough to decide that these tasks are not worth doing!

But with the advent of learning algorithms today, and their inevitable improvement, will absolute control of AI programs even be possible in later years? Stanley G. [Grauman] Weinbaum was one of the first to describe intelligent beings in the solar system [Weinbaum 1934] with intelligence fundamentally different from (even unintelligible to) human beings. This strikes at the heart of the grand dream of AI; intelligence is not necessarily an imitation of human thought processes. This raises issues such as this: if advanced AI is used on a long space mission, and its knowledge is altered greatly during its duration, we might not be able to comprehend its output after a certain point in time (assuming a suitable vast capacity to learn new concept). A related theme was the heart of the first *Trek* film, in which Voyager is redesigned into a super-intelligent entity by an alien being. If we replace the alien by advanced (albeit terrestrial) learning algorithms, the potential for the evolution of a craft's knowledge beyond our understanding is at least a possibility. Such a result occurred in the film *The Forbin Project*, based on the *Colossus* novel; humans stopped eavesdropping on the superintelligent computer once it evolved a language beyond our comprehension.

Another way we might interact with our machines is by merging with them to become **cyborgs** -- cybernetic organisms -- a term invented by science fiction [Caldin] and now in general use. In particular, *The Ship Who Sang* [McCaffrey 1961] and "Scanners Live in Vain" [Smith 1963] posit the need to mechanically alter humans profoundly in order to make long-duration space flight feasible. This point of view represents a worst-case analysis, if the problems of weightlessness cannot be overcome by more conventional means (e.g., [Post 1992] argues that all it takes to avoid the biological hazards of zero gravity is to be overweight, aerobically unfit, and have high blood pressure). Another possible advantage of having humans in more direct, detailed contact with machines is greater control over how the software's knowledge evolves -- such as keeping human goals, like relevance and explainability, paramount over those the AI software might have.

Note that there is another variant on this human-machine coupling idea. [Platt 1991] examines the implications of **downloading** a human mentality into a semiconductor substrate. Perhaps future criminals, rather than face execution, might be downloaded into space-AI systems for exploring the solar system [Jennings 1989]. Of course, downloading might require slicing and destroying the original human brain, and robots might not understand why people resist such an approach to immortality [Rucker 1982]. (At least we'd still be "alive"...right?)

But remember that the need for many space travel "solutions", such as altering humans, could be eliminated if, as we mentioned near the beginning of this section, we employ remote space exploration us AI. In this regard, an irony exists in one of *Trek's* most intriguing "inventions" -- the **holodeck**, a hypothetical combination of Virtual Reality and AI (a synthesis that one author coined VRAI [Post 1990], the French word for "truth"). In a holodeck, one can sample alternate worlds (VR) as well as interact with characters in that world (AI) that can be programmed to one's wishes. Such technology is not that far off from (real) reality today, and its advantages would be numerous for space domains. For instance, an astronaut -- *or even an Earth-bound* **"teleexplorer"** -- could try out fixes to spacecraft hardware in a holodeck *without having to alter the actual device*. In addition, stored technical experts could be "called up" out of digital hibernation and consulted even if they are physically distant (e.g., deceased). Note that an artificial expert could even be a composite of several people's knowledge and interpersonal styles -- a being who *never actually existed* in the real world (in that particular "configuration"). It is ironic that the holodeck idea, developed for use on a (fictitious) space vessel, might one day be used to enable humans to avoid actual travel at all (and perhaps may make the notion of large spacecraft obsolete). If this permutation of the initial holodeck intent eventually gets used for teleexploration, it would not be the first time an SF idea led in a nonlinear path to real payoffs. (Besides, who would have watched "Star Trek: The Stay-at-home Generation"?)

Finally, we note that the interaction between SF and real science is quite alive at the present time. One of the authors of this paper (JVP is acknowledged in [Platt 1991] for "advice on the policies and procedures of aerospace contractors", an example of how *science fiction and space AI do influence each other*. In addition, the profits from a book on how artificially intelligent solar sails may travel through or beyond the solar system will be supporting a real space flight [Post & Bradbury 1991]. Other examples abound.

Conclusions and Final Thoughts

Where will the "real" future lead us?

Given the above examples, scenarios and discussions, certain trends are more prevalent than others, and we can venture some final predictions, adding to those already presented.

The trend in robotics and AI software for space can be summarized with key words such as **small, cheap, flexible, adaptive** and **autonomous**, as well as **large numbers, redundancy, decentralized intelligence, remote operation** and **global teleaccess**.

Also, as the applications described earlier become increasingly common, powerful, and less expensive, **synergy** seems inevitable.

In both robots and AI software, the use of autonomous independent **intelligent agents** should enable an increasing number of functions to be performed continuously, with little human intervention. Such agents would be the software analog to the dumbots, in that they would represent specific specialized collections of knowledge and processes that "live" on their own, gather their own input, and communicate (to other software or to humans) when the appropriate conditions arise.

Machine learning methods should allow these agents to improve their behavior during long missions. In fact, **learning** will prove essential to deal with the unknowns of unexplored space, since no mission planner can predict all required system reactions, and instructions from Earth are impractical for long distant missions.

In time, fewer astronauts should be required per mission, increasingly replaced not only by telepresence equipment but by "astronauts on a disk". Such **"astrobots"** would have all the usual stereotypical benefits of automated workers -- more vigilant, more efficient, no sleep requirement, faster, able to fee any astronauts for other tasks, etc. The longer the duration of future missions, and the higher the chance of danger, the more valuable these automated astronauts would be to the success of such missions. In summary, astrobots should reduce human risk by decreasing the number of humans required for a given mission, and by allowing those remaining (if any) to perform tasks with greater safety and probability-of-success -- via consultation of automated expert systems, telepresence using the ship as the base (e.g., when Earth links are not feasible), and other techniques.

Perhaps Domino, the robot in *Michaelmas* [Budrys 1978], puts it in a more imaginative light:

"My bones are made of steel
The pain I feel is rust.
The dust to which your pangs bequeath
the rots that flourish underneath
the living flesh is not for me.
Time's tick is but the breathing of a clock
No brazen shock of expiration tolls for me.
Error unsound is my demise.
The worm we share is lies."

In summary, we presented several examples -- a survey of ideas and technologies -- to illustrate where AI has been applied in the past, some of today's issues, and ideas regarding how it might be applied to space missions of the future. AI should enable an increasing number of future missions to pose reduced risk to human lives, increase the amount of exploration that can be done without leaving Earth, and enhance the effectiveness of missions in which we or our surrogates go where no one has gone before.

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NOLOGY SYMPOSIUM

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r of 1999, the United States, in cooperation with its partners, launches its first a twenty-five ton lunar habitat, to the site selected for an initial lunar outpost, This habitat is activated from Earth, connected into the existing base complex *nis* missions, and shielded from natural radiation by placement of regolith into e end of the third quarter of 1999, telemetry confirms that this habitat is ready hat five tons of lunar oxygen are in storage. Readiness to return people to the

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cond crewed mission is launched, carrying four people and 5,500 kg of cargo ncludes science experiments and major augmentation of the lunar materials . In particular, equipment to correct shortcomings of the lunar oxygen and transfer complex is delivered and installed. Dust control installations are ved.

of their forty-two-day stay, a second large cargo delivery of twenty-five tons e 31st anniversary of the *Apollo 11* touchdown), including an operational-scale d processing complex. The third and fourth nuclear electric generating plant and are activated with the help of the crew. This crew returns to White Sands

~ **Clark** gave his views on the rationale, history, and future of the exploration of Mars, and ... between the common and unique technologies that must be developed for use on the ... Mars, as a consequence of the similarities and differences of the two planetary ...ated.

...f the NASA Johnson Space Center Solar Systems Exploration ...sonal participation in the reception and cataloguing for scientific ...mens, returned to Earth by the Apollo 11 mission almost twenty- ...the use by investigators today of a national treasure -- the 400 kg ...were returned by Apollo -- regularly obtaining new scientific and ...hly relevant to the technology issues of future lunar resource

...oup on the progress made in the past few years by advocates of lunar ...ested that, with the release of the "Synthesis Group" report, this topic ...ning by policy makers for an early return to the Moon. He suggested ...nar materials utilization, turn our attention from describing the far future ...p the specific near-term implementation plans, including identifying and ...chnology development. He pointed out the necessity for those of us ...rces to communicate effectively with one another and with others, carefully ...work to assure that research results are critically reviewed and, after ...istributed to be built upon by others.

... goals for lunar materials use should be that lunar oxygen is used for the very ...ple return missions and that, additionally, lunar hydrogen and other useful ...d from the solar wind-implanted volatiles, only a short while later, to provide the ... will enable us to lower the cost and risks to humans on the earliest piloted

"Strawman": A Near-Term Materials Utilization Plan

...urn to the Moon as called for three years ago by President Bush are now underway ...al Space Council, chaired by Vice President Dan Quayle, and a new National Program ...ce Exploration is being formed, headed by Mr. Mike Griffin of NASA. This multi-agency ...management office will include representatives from a broad spectrum of the United ...ernment, including NASA, the Department of Defense, and the Department of Energy; ...al participation is being encouraged and explored.

...andidate "architectures" for a return to the Moon have been defined by NASA, but no single ... yet emerged for beginning this multi-faceted venture. Under these circumstances, there ... no master plan to that we can refer to in order to plan our near-term activities. The best ...n be done now is to encompass a range of prospective plans in our thinking, to enable us ... only respond to policy as it emerges, but in fact to help shape it.

...isk of being too bold in our planning is probably much less than the risk of failing to exploit, ... to point out to policy-makers, the real opportunities for effective use of lunar materials in ...suing national goals. Thus, an aggressive near-term scenario, which may be thought by many ...be unrealistic in today's Federal Budget environment, is considered to be an appropriate present stance for the lunar materials research community. As policy decisions are made, we must then support them.

Time Frame to be Considered

The long-term future of the use of lunar materials is provocative and compelling. Many of us view the future of humankind, perhaps three to five generations from today, as materially rich, with all of the people of Earth enjoying abundant and inexpensive energy from space, through construction of Solar Power Satellites (SPS) largely from lunar materials, and/or from importing ^{3}He from the Moon to power future, clean fusion reactors, and perhaps from huge solar power plants built on the lunar surface "beaming" their energy to hundreds or thousands of locations on Earth. Earth-crossing asteroids may also be captured and their material resources applied to extensive human activities in space, for the enrichment of people on Earth.

These gigantic projects have been found to be within the realm of technical feasibility, given the technological advancements of the past fifty years and those that can be responsibly forecast for the next fifty years. Their comparative economics, however, require consideration of much broader issues and are not yet nearly so clear. In large part, the internal problem of assessing these prospects is forecasting the time and other resources necessary for their development and acquisition.

Favorable economics can be forecast only through "bootstrapping" -- beginning small and emerging to large scale through internally supported growth. Solar Power Satellites, for example, to be affordable must be built largely of materials already in space; that is, on the Moon.

We cannot, however, expect society to provide a fullblown SPS production infrastructure on the Moon and in space -- it must grow through internal efforts. For this reason, the planning horizon of the following scenario is 2015.

A Mission Scenario

One of many possible mission scenarios is described below. At this time, it has to be considered only a reasoned speculation. It will prove to be a deeply flawed forecast in many important respects, but has as its purpose the generalized scoping of what could be the size and intensity of lunar materials use during the first two decades of the new millennia, for helping to identify the sequence, timing, and scale of lunar materials technologies.

During the 1994-1997 interval, three lunar polar orbiter (LPO) missions, each returning data for over one year, are flown. These spacecraft return multi-spectral imagery and specialized sensor data to Earth, allowing, for the first time, global mapping of the lunar features and resource concentrations discernable from a 100 km orbit.

Russia, along with three of its neighboring republics, supplements these data with a lunar polar orbiting radar spacecraft. Project *Artemis*, funded by NASA, begins placing 150 to 200 kg science and technology payloads on the Moon's surface in 1994. Thirty such missions are planned, at the rate of six per year, to reconnoiter four landing sites selected as candidates for an early lunar outpost.

Each complex of payloads includes a sensor- and grappler-equipped miniature "rover" with 10 km range; a utilities spacecraft providing electrical and thermal power, heat rejection, and communications services; a science module providing geo-physical capabilities for sample assay; a subscale regolith movement and classifying suite; and a pilot plant lunar oxygen generation plant. Early success leads to an expansion of this program with three additional flights, beginning in 1996, to return samples from two of the selected sites.

In 1997, *Artemis II* flights begin to put in place two-metric-ton astronomy payloads and "pilot plant" facilities at one of the sites. Six such flights by mid-1998 provide the capability to generate and store up to five tons per year of liquid oxygen at this site. Russia provides two nuclear reactor electrical power supplies and four *"Lunakod II"* rovers to augment these capabilities, equipped with advanced manipulator systems provided by Canada and "virtual reality" capabilities from U.S. universities. ESA and Japan join in, providing advanced lunar materials pilot plants to separate metals, formulate useful ceramic materials and semiconductors, to produce finished products from the heated "tailings" of the oxygen plants, and prove processes for the deposition of amorphous silicon and electrical conductors on plastic film brought from Earth. Other payloads are delivered and automatically erected to produce 3 MWt of high quality concentrated solar energy and to reject an equivalent heat load. By 1999, an automated surface complex aggregating over twenty tons is in place at this site. *Artemis* sample return flights continue to return samples of materials produced and for tests of failed components.

In the second quarter of 1999, the United States, in cooperation with its partners, launches its first large lunar payload, a twenty-five ton lunar habitat, to the site selected for an initial lunar outpost, *Lunar Base 1* (*LB-1*). This habitat is activated from Earth, connected into the existing base complex provided by the *Artemis* missions, and shielded from natural radiation by placement of regolith into prepared bins. By the end of the third quarter of 1999, telemetry confirms that this habitat is ready for occupancy, and that five tons of lunar oxygen are in storage. Readiness to return people to the Moon is declared.

Late in 1999, the first piloted mission arrives at *LB-1*, and the crew immediately occupies the fully shielded habitat, using the utility services pre-placed by *Artemis*. The 5,500 kg payload carried on this mission includes an unpressurized "rover" with 30 km range, science experiments requiring human placement, and spare parts to restore to operation three malfunctioning *LB-1* functional units. Extensive surface geological surveys are conducted by the two planetary geologists on the mission using the rover and assay facilities previously placed. The automated equipment on the Moon is controlled by the civil engineer of the first crew to prepare thin glazed surfaces and to lay fused regolith blocks for future flight and surface vehicle operations areas to help control otherwise intolerable lunar dust formation. Near the end of the forty-two-day surface stay, a portion of the stored lunar oxygen is transferred by the crew into a tank of their Lunar Landing Vehicle (LLV), which is to be left behind. Refinement of oxygen loading procedures and noting equipment shortcomings for future correction are the purposes of this experiment.

The crew then ascends into lunar orbit, conducts final lunar orbit observations and four days later enters the Earth's atmosphere, soft landing by maneuverable parachute near White Sands, New Mexico, on President's Day, 2000.

In June 2000, the second crewed mission is launched, carrying four people and 5,500 kg of cargo to *LB-1*. The cargo includes science experiments and major augmentation of the lunar materials processing complex. In particular, equipment to correct shortcomings of the lunar oxygen production, storage, and transfer complex is delivered and installed. Dust control installations are expanded and improved.

During the latter part of their forty-two-day stay, a second large cargo delivery of twenty-five tons arrives on July 20 (the 3lst anniversary of the *Apollo 11* touchdown), including an operational-scale regolith gathering and processing complex. The third and fourth nuclear electric generating plant arrive during this stay and are activated with the help of the crew. This crew returns to White Sands on August 4, 2000.

An interval of automated operation of *LB-1* then begins, and major new mission plans are refined. Two objectives are selected: expansion of the capabilities of *LB-1* to include a permanent human presence with pressurized rovers, and establishment of extensive automated sorties to the lunar north polar region, supported by observers in lunar orbit.

To satisfy the first objective, it is found that 500 tons of additional cargo must be delivered to *LB-1* by 2015 and an additional fifteen piloted missions flown. Piloted mission (PM) return by use of stored lunar oxygen is committed for PM-4 and subsequent missions, allowing the lunar vehicle to carry sixteen tons of cargo on each mission as well as the crew and their return flight vehicle. Product improvement of the vehicle increases cargo mission (CM) capability to 30 tons per mission. The flight manifest now includes PM-3 through PM-17 and CM-3 through CM-12, as well as an additional ten *Artemis II*, twelve Russian, five ESA, and four Japanese automated flights.

Through these efforts, a permanent crew of eight persons is in place at *LB-1* by 2012, with crew rotation intervals averaging once per year. Six sites have been thoroughly explored and surveyed for future lunar industrial complexes. One of these sites is a major iron-nickel deposit, similar to that in Canada, that will be exploited for its metals.

Another site is rich in ilmenite and expected to become the hub of a global lunar oxygen pipeline system. Third and fourth sites near the lunar limbs are under review as major solar power generation sources, with major activities expected there in producing thin film solar arrays, aluminum, and foamed glass structural elements. The final two sites have been found to be unusually rich in solar-wind implanted volatiles and are to become, by 2020, the first of a series of "standard" 50-million-ton-per-year mining and processing centers, each with a crew of fifty persons.

Thus, by 2015, all preparations have been made for lunar resources to supply materials to all human space activities, including exploration of Mars, and to begin to put into place the large SPS and other energy sources for the people of Earth.

Within these activities, which can occur over a span of the next twenty years or so, have progressed major technology activities both to enable these events to occur and to enhance their productivity and return on investment.

Contribution to the Panel Discussion

John S. Lewis
University of Arizona/NASA Space Engineering Research Center

As we contemplate the possible futures of America's (and the world's) space efforts, I feel that we must take renewed interest in presenting our case to the public and to Congress. It may well be that *all* future space activity, especially long-term exploration, may rest upon demonstrating direct, short-term benefits to Earth. Expensive items such as Space Station Freedom, the Lunar Base, and Mars expeditions will be especially hard to sell unless they contribute visibly to a coherent plan for using space to the benefit of humanity. But if it is perceived that large-scale space activities can contribute to the material good of mankind, then basic research and the exploitation of space resources to defray the cost of in-space activities will also be seen as visibly serving the public good.

We should begin at once to emphasize the importance of early, careful assessment of a wide range of future options. It is tempting in dealing with the public to commit the error of excessive concreteness by championing a single scenario long before we know whether it is the most desirable. Such a lapse, in which we prematurely advocate a dud, could be the demise of space exploration and exploitation alike. The public attitudes fostered by the *Challenger* disaster, the Hubble mirror debacle, the Galileo antenna episode, etc. predispose the electorate to expect bumbling incompetence from NASA. They are perilously close to shutting down all that is good in space because of these highly visible gaffes. I can envision the public leaping at the lunar ^{3}He answer to Earth's energy problems, only to find out $100 billion later that this solution might not prove economically competitive.

As part of this opening of the debate about goals in space, clearly one of the most important things we can do is to provide the public a variety of new ideas (new, at least, to them) that merit early, relatively inexpensive assessment. The issues we raise should include the best source of materials for Solar Power Satellites and where to build them, laboratory assessment of D-^{3}He fusion to establish its scientific and engineering feasibility, and a comparative study of sources of ^{3}He fuel. We should also explore the retrieval of non-terrestrial precious and strategic metals for use on Earth, but the public is interested mainly in cheap, clean, abundant, and environmentally benign sources of energy.

There are certain obvious problems that confront humanity at this juncture, such as global warming, radioactive waste handling, the stability of the ozone layer, and acid rain from combustion products. Such projects are clearly of global importance. They are excellent vehicles for international collaborations of all kinds, in which the American scientific and technical communities can play a vital leadership role. But it is well to remind ourselves that this is also a time of tremendous opportunities. First, there is the issue of conversion of the military technology base of the Western nations to civilian pursuits. The cutting edge of Western science and engineering, traditionally whetted by military requirements, must be kept sharp in order to keep our industries competitive in world civilian markets. This industrial restructuring (better called *perestroika*) demands that a civilian niche be found -- to occupy the talents of the highly skilled aerospace engineers who gave us victory in the Cold War. The logical place for such people is in a technically demanding, high-tech attack on the great problems listed above.

At the same time, the emergence of democratic governments in the fifteen republics of the former USSR and in the newly liberated nations of Eastern Europe, combined with their acute economic peril caused by seventy-four years of centralized planning and militarism, have led to the entry of a host of challenges. First, there is the much-discussed problem of what to do to prevent former Soviet nuclear weapons designers from emigrating to nations with more money than morality. In recent weeks both the American and former Soviet nuclear rocket and scramjet research programs have been declassified. It is to the mutual advantage of all countries that desire peace to see these capabilities used for civilian programs that benefit mankind. Civil space endeavors are the obvious response to this new openness (or *glasnost*) of previously classified programs.

The explorational basis for the use of materials from the Moon and other bodies is well understood: the data desired by "pure science" and by resource advocates have a large overlap. The basic science need for compositional and structural mapping of the Moon and the basic engineering need for data on the behavior of real lunar materials during physical and chemical processing in the lunar environment are well known and need not be itemized again here. The Lunar Observer program admirably addresses both sets of needs for chemical and physical mapping of the Moon. The *Artemis* program, as presently envisioned, promises an inexpensive series of missions to serve both scientific and engineering purposes, with low costs linked to frequent flights and quick response to emergent opportunities. A well-managed program of this type is automatically responsive to changing needs and interests that result from new knowledge. This amounts to a rediscovery of the "good old way" of conducting exploration: a return to the days of the Explorer, Luna, Mariner, Venera, and Pioneer program philosophies that opened the Solar System to us in the 1960s and 1970s. Obviously this approach is not limited to the Moon: similar design philosophies should also be applied to Mars-system and asteroid missions.

There is no shortage of talent in America, no dearth of scientific curiosity or engineering know-how. We have pioneered every subject of interest here, from lunar exploration to asteroid science to the search for life on Mars; from Solar Power Satellite design to ^{3}He retrieval to non-terrestrial strategic metals recovery. We have all the requisite strengths -- but somehow we cannot bring ourselves to exercise these strengths. Many years ago, Victor Hugo contemplated this dilemma of human nature and explained it thus: "Man does not lack strength -- he lacks will." The will of a democracy, or of a community of democracies, can be expressed by the people. But if anything is to happen, there must be leadership, a visible, public expression of will. That is what we are lacking.